Renewable and Sustainable Energy Reviews 32 (2014) 468–476

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Evaluation of technologies for harvesting wave energy in Caspian Sea

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ARTICLE INFO

Article history:
Received 2 September 2013
Received in revised form
12 December 2013
Accepted 4 January 2014
Available online 1 February 2014

Keywords:
Caspian Sea
Wave energy
Point absorber

ABSTRACT

Ocean is one of the renewable sources of energy that can supply part of the world's energy needs and thus reduce the rate of consumption of fossil fuels and other non-renewable resources. The wave energy can be converted to electricity or other forms of usable energy. Water waves have a relatively high power density with a total global power of approximately 1–10 TW, equivalent to a large fraction of the world's current total energy consumption. This study is aimed at evaluating the existing systems for converting the wave energy into electricity with the idea in mind that they could be used in the Caspian Sea, with average wave energy of 5–14 kW/m. To achieve this, major devices in this field along with the most important design parameters are identified and analyzed. Each existing system's main features are presented in a benchmark table, where each feature is assigned a weighting factor. The total score for each energy extraction system is then obtained. The most suitable device is chosen based on the conditions of the Caspian Sea including amplitude, wavelength and frequency of the waves, the depth of the sea as well as the seabed and shore conditions. The performance and maintenance costs of the device have also contributed to the final selection. Based on the current study, point absorber wave energy converters are the most appropriate devices for harvesting wave energy in Caspian Sea.

Contents

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http://dx.doi.org/10.1016/j.rser.2014.01.036

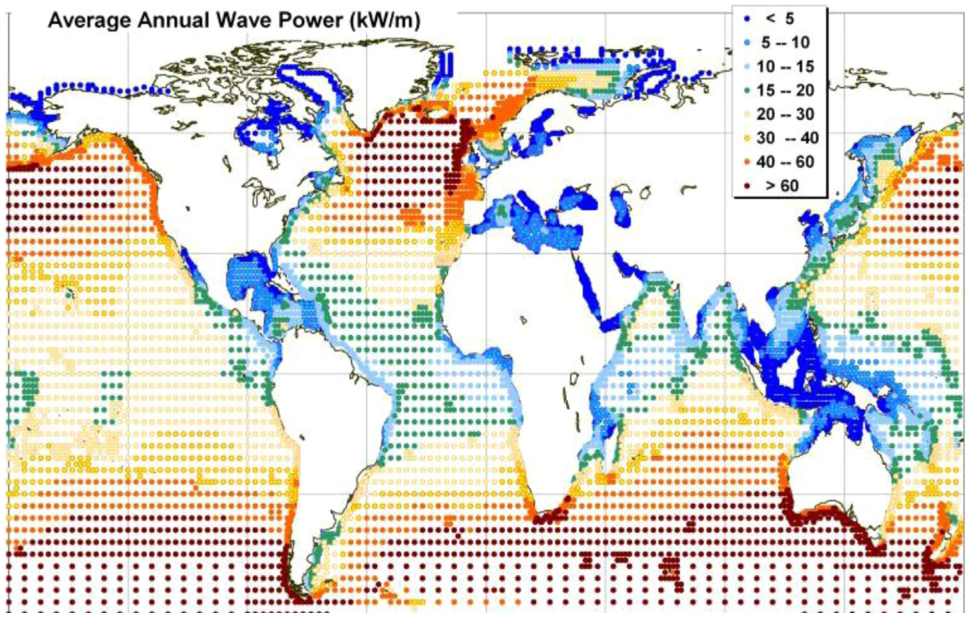


Fig. 1. Worldwide average wave power potential (kW/m) [33].

1. Introduction

The growing need for energy, scarcity of fossil resources, and environmental pollution due to fossil fuels along with the impacts of global warming on human life have drawn attention towards renewable energy resources. Ocean wave energy is one of the cleanest form of renewable energy. Salter's article [1] in Nature was perhaps the turning point in attracting the international scientific community to the wave energy. Many efforts have since been made to extract this potential energy. Fig. 1 shows the distribution of potential wave energy in the world. Wave energy technology is still in its infancy, the situation that wind energy technology had more than 20 years ago. A number of obstacles are yet to be overcome to make full use of this energy source. Over past few decades, extensive research has been made in the field of wave energy conversion [2,3]. Wave energy has been reviewed by a number of investigators including McCormick [4], Charlier and Justus [5], Ross [6], Brooke [7] and Cruz [8].

Caspian Sea has great wave energy potential, yet it has not received attention by researchers and investors. Mediterranean Sea with a mild wave energy climate [9] has been studied by many researchers to extract its wave energy. Likewise, the region between Balearic Islands and Sardinia with a maximum wave energy potential of ~15 kW/m [10] has been a favorable site for many years. Caspian Sea is situated where the south eastern Europe meets the Asian continent, between the latitudes of 47.13°N and 36.34°N and the longitudes of 46.43°E and 54.51°E [11]. This Sea is bounded by Iran in south, Turkmenistan and Kazakhstan in east and north east, Russia in north west and west, and Azerbaijan in west. It has a coastline length of about 7000 km. The Caspian Sea is relatively wild most times of the year, due, in part, to the direction of the winds. This raging sea has extremely large potential for wave energy. Although the Caspian Sea is a closed water basin, due to its large surface area and depth as well as its diversified weather systems, it is exposed to storms and elevated winds most of the time. Caspian Sea has an average and maximum wave power of 14 kW/m and 30 kW/m, respectively [12].

The objective of this study is to identify the most suitable system for extracting wave energy in the Caspian Sea. Wave energy system for a site is usually selected based on several important criteria including the status of the sea/ocean, manufacturing technology, installation and maintenance of the mechanical and electrical equipment as well as the efficiency of the device. The Caspian Sea has relatively soft seashore and its bed is made of soft silica, making it inappropriate for oscillating water columns or overtopping systems. Given that this sea is salty, an appropriate system should be one with a high corrosion resistance. In addition, the moving mechanical parts are preferred to be sealed to keep the maintenance costs low. Having all these in mind, among the most efficient wave energy conversion systems, a point absorber-type converter is most suitable for the Caspian Sea.

2. Existing wave energy extraction technologies

Major research and development of wave energy converters began through a number of programs in Great Britain in 1975 [13]. These programs were then followed by the Norwegian government. In 1985, major efforts were made towards the construction of two real size converters with the rated power of 350 kW and 500 kW on a coast near Bergen, Norway. Until the early 1990s, activities in this field remained at the academic level in Europe mainly. The most notable achievement of this period is a small scale 75-kW oscillating water column (OWC) based in Islay, Scotland, in 1991 [14]. Around the same time, two OWCs were built in Asia, including a 60-kW converter integrated with a breakwater in the port of Sakata, Japan [15], and a 125-kW bottom-standing power plant in Trivandrum, India [16]. The 2-MW converter in Scotland, destroyed by the waves, is among the unsuccessful systems of the time.

In 1999, a 400-kW OWC was deployed in Portugal followed by a 300-kW Limpet in Scotland in 2000 [17]. The floating point absorber SEAREV was first introduced in France in 2003 [18]. Two years later, a newer version of this absorber was launched in Port Kembla, Australia [19] and a semi-industrial 1:5 scale prototype, called Wave Dragon, was thrown into the water in Denmark [20]. In 2006 and 2007, a number of OWCs were installed in Sweden, Spain, and in the state of Oregon in USA. Later in 2008, other converters were launched including a Pelamis in northern Portugal [21], 16 OWC systems in Mutriku, Spain [22], and a floating system at the Oregon State University [23].

Table 1
Characteristics of attenuator wave energy conversion systems including OceanLinx [39], Limpet [17,40], Pico Plant [41,42], Osprey [43], and Mighty Whale [44,45].

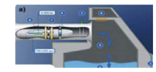
Wave Absorber	Type, water depth (m)	Mean wave power (kW/m)	Output power (kW)	Generator position	Photograph
OceanLinx	Floater off-shore 5–50	50	200–1500	Above free-surface	
Limpet	Fixed on-shore 15	15	500	On-shore	
Pico Plant	Fixed in the ocean 7	40	400	Above free-surface	
Osprey	Fixed in the ocean 15–20	50	500	Above free-surface	
Mighty Whale	Fixed ocean surface 40	15	110	Above free-surface	

Table 2
Characteristics of oscillating water column wave energy conversion systems including Pelamis [46], Wave Star [47], Salter Duck [48] and Anaconda [49,50].

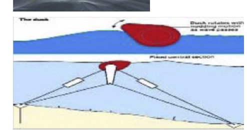
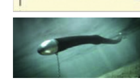
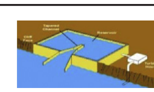
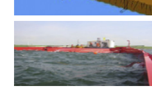
Wave absorber	Type, water depth (m)	Mean wave power (kW/m)	Output power (kW)	Generator position	Photograph
Pelamis	Floating ocean surface 50–60	15–40	750–1000	Within the body	
Wave Star	Floating In the ocean 2–30	24	500–6000	Over water surface	
Salter Duck	Floating in the ocean 2–30	24	375	In water	
Anaconda	Floating in the ocean 20	50	1000	Out of water	

Table 3
Characteristics of overtopping wave energy conversion systems including Tapchan [51], Wave Dragon [20,52] and SSG [53].

Wave absorber	Type, water depth (m)	Mean wave power (kW/m)	Output power (kW)	Generator position	Photograph
Tapchan	Fixed shore 20	40	350	Out of water	
Wave Dragon	Floating ocean surface 20–30	24	40	In water	
SSG	Fixed shore 15	19	150	Out of water	

The 1:5 scale Wave Star in Denmark and the 1:4 scale WaveBob in Ireland are among the semi-industrial converters [24]. A 25-kW floating system was also designed in Denmark along with an Osprey in UK. In 2010, the Oceanlinx with eight air chambers and two turbines was introduced in Australia, followed by PSFROG in UK [25,26]. Salter energy converters (UK), point absorbers (Norway), tapered channels (Norway), energy absorbing pedals (Japan), and Archimedes buoys (Portugal) are among other devices that have been deployed to date.

There currently exist about 80 technologies for wave energy conversion. Wave energy conversion systems can be classified based on installation on the coast, sea or seabed. They can be classified into four major categories: oscillating water columns, overtopping systems, attenuators, and point absorbers [27–31]. A brief description of each category is presented below.

2.1. Oscillating water column

Oscillating water column (OWC) systems are made in both fixed and floating models. Their function is much like a wind turbine such that a closed air chamber is placed above the water level. As the wave runs around the device, the water level in the chamber changes, altering the pressure of the internal air. At the top of the chamber, there is a turbine that is rotated by the pressurized air. When a wave moves up, air is expelled out and when the wave moves down, air is

Table 4
Characteristics of point absorber wave energy conversion systems including SEAREV (France) [54], L10 Buoy (Sweden) [31,55], OPT Power (UK) [56], AquaBuoy (Canada) [57,58], Archimedes Buoy (Scotland) [59,60], Uppsala (Sweden) [61,62], WaveBob (USA) [63,64], WaveRoller (Finland) [65], BioWave (Australia) [66] and Pendulum (Japan) [67].

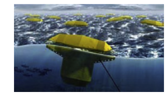
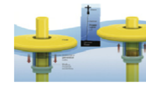
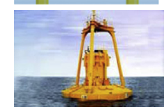
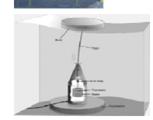
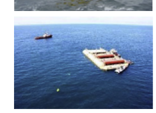
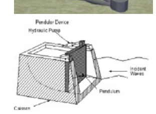
Wave absorber	Type, water depth (m)	Mean wave power (kW/m)	Output power (kW)	Generator position	Photograph
SEAREV	Floating ocean surface 50	40	500	On the ocean surface – inside the body	
L10	Floating in the ocean	20	10	In water – inside the body	
OPT power	Fixed in the ocean 30–60	50	40–500	In water – inside the body	
AquaBuoy	Fixed Ocean surface 40–80	15–50	250	On the ocean surface – inside the body	
Archimedes Buoy	Fixed seabed 30–60	15	250	In water	
Uppsala	Fixed seabed	20	5	In water	
WaveBob	Fixed ocean surface over 50	20–70	500	In water	
WaveRoller	Floating seabed 6–23	15	300	Shore	
BioWave	Fixed seabed 6–23	50	250–1000	In water	
Pendulum	Fixed shore	15	20–300	Out of water	



Fig. 2. A three-dimensional model of the Caspian Sea [34].

sucked in. Wells turbines are used in these devices to allow for rotation of the shaft in one direction regardless of the direction of the air flow. These devices produce an annually averaged power of 15–25 kW/m. Oceanlinx, Limpet, Pico plant, Osprey, and Mighty Whale are among the existing OWC wave energy converters. Table 1 presents a brief description of these converters.

2.2. *Attenuator*

Attenuator systems are deployed such that they face the incident waves. The waves stimulate a series of mechanical components, which in turn operate an electricity generator. These systems are usually attached to the sea floor. Examples of this

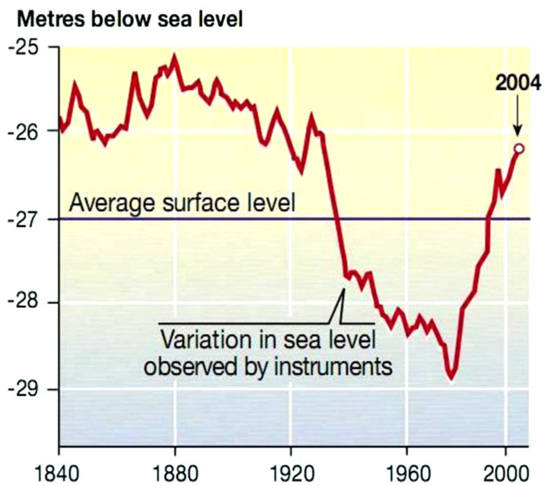


Fig. 3. Caspian Sea water fluctuations for a 164-year period [35].

Table 5
Caspian Sea water pH level [68].

Basin	Depth (m)	pH
South	0	8.46
	100	8.29
	600	8.04
	800	8.01

category include Pelamis, Wave Star, Salter Duck, and Anaconda. Characteristics of these systems are presented in Table 2.

2.3. Overtopping device

Overtopping systems are partially submerged in water, allowing the incoming waves to pour into a tank. The water will then drive a turbine to produce electricity. Tapchan, Wave Dragon, and Sea-wave Slot-cone Generator (SSG) are among these devices. These systems are briefly described in Table 3.

2.4. Point absorber

Point absorber systems extract energy from the swinging motion of the wave. They can be partially or fully immersed. Examples of this category include OPT Power (USA), L10 Buoy (Sweden), AquaBuoy (Canada), Uppsala (Sweden), Archimedes Buoy (Scotland), SEAREV (France), WaveBob (USA), WaveRoller (Finland), BioWave (Australia) and Pendulum (Japan). Table 4 presents the characteristics of these devices.

3. Caspian Sea

Caspian Sea is the largest lake on the earth with a surface area of 436,340 km^2. This sea has a depth of about 180–1000 m in the southern basin and 2.6 m in the northern basin. The central basin is deeper than northern basin with an average depth of 175.6 m and a maximum depth of 768 m. A three-dimensional model of the Caspian Sea is shown in Fig. 2. Important factors influencing the selection of a wave energy converter for this sea include the water level fluctuations, chemical composition, climate, and the wave energy potential, which are briefly described below.

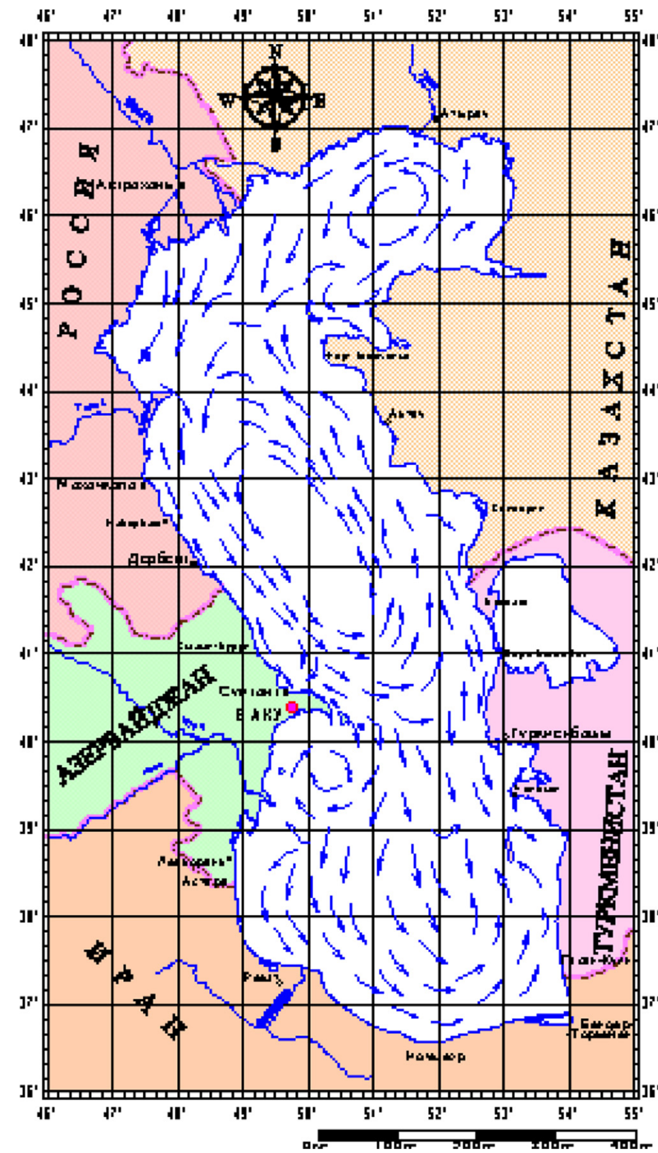


Fig. 4. Circulation of water in the Caspian Sea [36].

3.1. Water level fluctuations

Gravitational forces, winds, waves, changes in air pressure, and quantity of water entering its rivers are among the main factors that cause water level fluctuations in the Caspian Sea. Migration of organics and sediments is also important. Variations in temperature and salinity of the sea water can alter the water volume. An increase in water temperature will result in an increase in evaporation and thus the water salinity. River and ground waters entering the Caspian Sea, rainfall and evaporation from the surface of the sea and water withdrawals are the most important factors balancing the volume of the water in the Caspian Sea. Among the above factors, evaporation from the surface of the sea and the discharge of the Volga River are more influential than others. In addition, removing water from the basins for municipal, industrial and agricultural uses as well as evaporation from the dam lakes significantly affect the water level. Fig. 3 shows the Caspian Sea water level fluctuations for a 164-year period.

3.2. Chemical composition

Chemical composition of the sea plays an important role in the selection of the materials for the wave energy converter. The

Caspian Sea has a salt level between 12 and 13 g/L, increasing from north to south and from west to east. As the water depth increases, the salinity of the water slightly increases, resulting in significant mixing of surface and deep waters. Caspian Sea's water salinity is approximately one third that of open waters. Furthermore, the hydrogen ion concentration at different parts of the central and southern basins changes from 3.8 to 6.8 near the surface and from 7.7 to 8.0 around the seabed. Table 5 shows the level of pH in the southern basin of the Caspian Sea. This area has a pH level of approximately 8.45. Magnesium, calcium and sulfate are among other important constituents. Heavy metals are also found in the Caspian Sea including arsenic, nickel, chromium, mercury and copper. Due to the lower level of corrosive compounds in this sea compared to open waters, a wider range of materials can be used for wave energy converters.

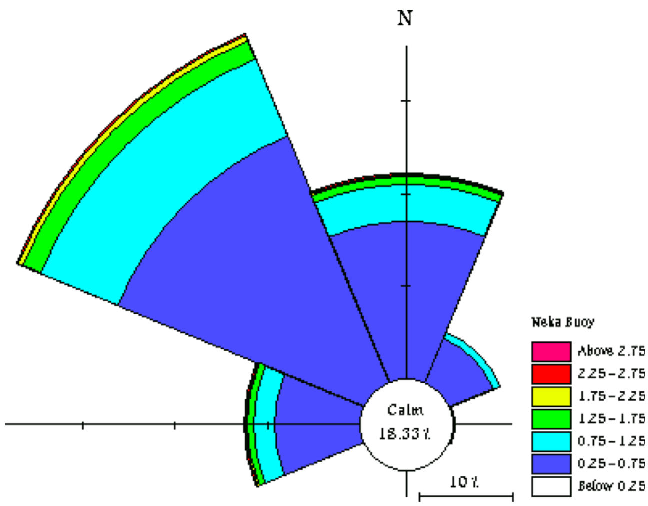


Fig. 5. Water height based on the data from the Neka buoy [37] in the Caspian Sea.

3.3. Climate

Given the extent of the Caspian Sea, it has a broad range of climates. On the southern part, the weather is Hyrcanian with relatively high rainfall and humidity. From west to east, the evaporation rate from its surface increases whereas the precipitation decreases. The annually averaged evaporation from the Caspian Sea (excluding the Gulf of Garabogazkol) is about 760 mm. During the cold seasons of the year, the Caspian Sea and the surrounding areas are affected by frigid and hyperbaric Siberian weather. However, in the warm seasons, the sea is influenced by the partial pressures of Azores, resulting in lower rainfalls.

3.4. Wave energy potential

In the Caspian Sea, there is a major rotational current with a counterclockwise motion as seen from the space. Fig. 4 shows the circulation distribution for the Caspian Sea. There are several buoys in the Caspian Sea to gather information about the wave

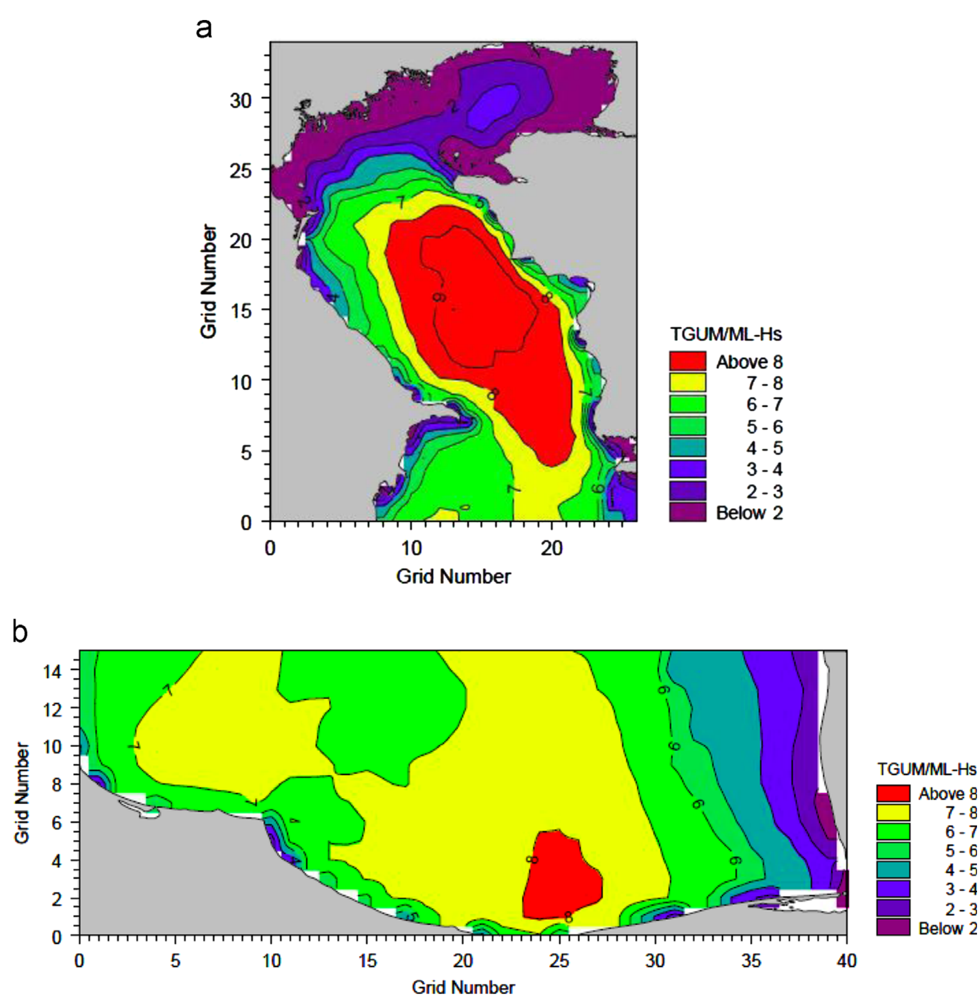


Fig. 6. Water height (m) in (a) northern and (b) southern basins of the Caspian Sea over a 100-year period. Data from EVA modeling [38].

including wave height and wave period, which are very important for estimation of wave energy in the sea. Fig. 5 shows the wave height measurements at the site of Neka for 12 years. In addition, a number of simulations were carried out based on the Extreme Value Analysis software (EVA). Fig. 6 shows the wave heights in the southern and northern basins of the Caspian Sea over a 100-year time period. H_s is the significant wave height in these figures. Based on these studies, the wave period varies between 2 s and 8 s in the southern basin of the Caspian Sea [12]. Also, the wave height changes between 0.5 m and 3 m in different seasons.

The wave power extractable from the Caspian Sea is estimated by the following equation [32]:

$$P = \frac{1}{64\pi}\rho g^2 H_s^2 T$$

where H_s is the significant wave height (m), T is the wave period (s), and P is the wave energy flux per unit of wave-crest length (W/m). Substituting $\rho = 1000$ kg/m^3 and $g = 9.81$ m/s^2 in the above equation, the power can be calculated as follows:

$$P = 479 H_s^2 T$$

Given the significant wave height and the wave period, the average wave power extractable from the Caspian Sea is between 5 kW/m and 14 kW/m.

4. Benchmarking

To achieve the goal of finding the most appropriate wave energy converter device for the Caspian Sea, a benchmark table is used to include the most important design parameters as well as the best available devices. The final decision was made based on this benchmark table and the conditions of the Caspian Sea. The parameters that affect the ranking of these devices are described below.

4.1. Power production

The amount of power produced by the device normalized by mass, volume, capital cost, or some other metrics is perhaps the most important decision making parameter. In most cases, the total power production of an energy farm is more favorable than the power output of a single device. Each of the wave energy conversion systems is assigned a score between 0 and 10 based on its power production and volume.

4.2. Sea conditions

The Caspian Sea has a relatively unstable bed. The main constituent of the bed is silica 100–500 m from the coast, where wave energy converters are preferred for installation. Surface winds can cause sedimentation movements on the bed of the sea. Studies have shown that seabed movements have a significant effect on the strength of the overpassing waves. This effect is also taken into account in the current evaluations. The range of wave power variations (significant wave height and period) has been determined by other studies and is used in the current investigation. The annually averaged strength of the waves in the Caspian Sea is approximately 5–14 kW/m. The existing systems are assigned a score between 0 and 10. A score of 0 is for systems that need to be rigidly mounted on the seabed, a score of 2 is for systems that are placed on the beach, a score of 5 is for floating and semi-immersion systems and a score of 10 is for systems that do not require seabed for their operation.

Table 6
Electrical system ratings.

Generator	Availability	Efficiency	Construction
Squirrel cage induction	10	7	–
Linear induction	2	5	5
Rotational induction	8	6	8
Linear synchronous	5	8	–
Rotational synchronous	5	10	10

4.3. Device installation

From the installation point of view, wave energy converters are either fixed or floating. It is important to seal the electrical systems as well as sensitive mechanical parts. In some wave energy converters, the device is semi-immersed with its mechanical components and turbine generators above the water free surface. This reduces the costs of sealing and maintenance. In others, part of the device floats while the rest of it is fixed to the bottom of the seabed. These latter devices require care for sealing. Oscillating water columns require a special air turbine that rotates in the same direction regardless of the direction of the inlet and outlet air flow. Due to the need for extensive infrastructures, oscillating water columns are not preferred in many applications. In some devices, a hydraulic system is used to pump a fluid, which in turn rotates a motor connected to a generator. The fluid has the advantage that it allows for smoother conversion of wave energy to electricity. Nonetheless, manufacturing such devices (e.g. Aqua, Pelamis, and Anaconda systems) are difficult. In spite of these difficulties, they have characteristics that make them beneficial over other systems. Systems such as WaveRollers that are deployed underwater require frequent maintenance.

4.4. Electrical system

Generators that are used in wave energy converters are one of the main components of these devices and are either linear or rotary. The generators are selected depending on the type of mechanical system in the converter. In the current study, the electrical systems were rated based on their availability, efficiency, and construction difficulties. The ratings that are used in the benchmark table are listed in Table 6. Availability is mainly characterized by parameters such as economic factors, costs of installation and service, ease of control and maintenance and dimensions of the device. The efficiency of the device is rated based on power output. Generators with lower energy dissipation are rated higher. Finally, manufacturing difficulties are rated based on the complexity and capital costs. The overall ratings are used as a guide to select the best system for the Caspian Sea.

5. Discussion

The benchmark table presented in this study takes into account a wide range of parameters to help identify the most suitable wave energy converter for the Caspian Sea. The most important parameters that form the benchmark table include installation, access to manufacturing technology, output power, availability of the electrical system, and construction of the generators, generator efficiency and security of the installation site.

Figs. 7 and 8 present the ratings and the total scores for each system. It is clear from the current evaluation that the best system for use in the Caspian Sea (specifically in the southern basin) is a point absorber device. The weather and wave conditions of this sea make the choice more reasonable. In addition, the point absorber technology has a lower complexity and easier access.

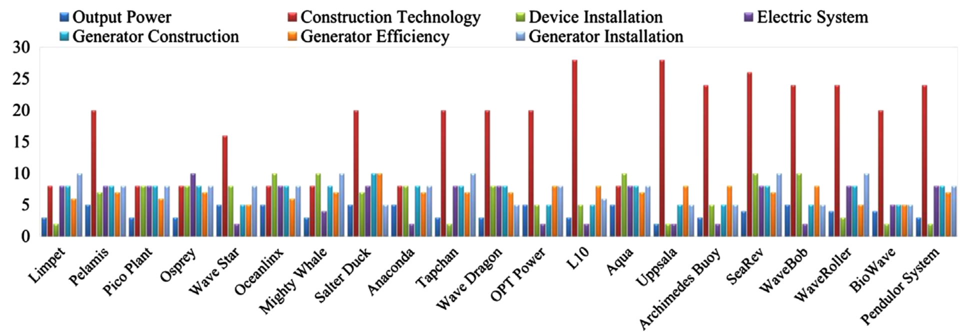


Fig. 7. Ratings for each wave energy converter parameter for use in the Caspian Sea.

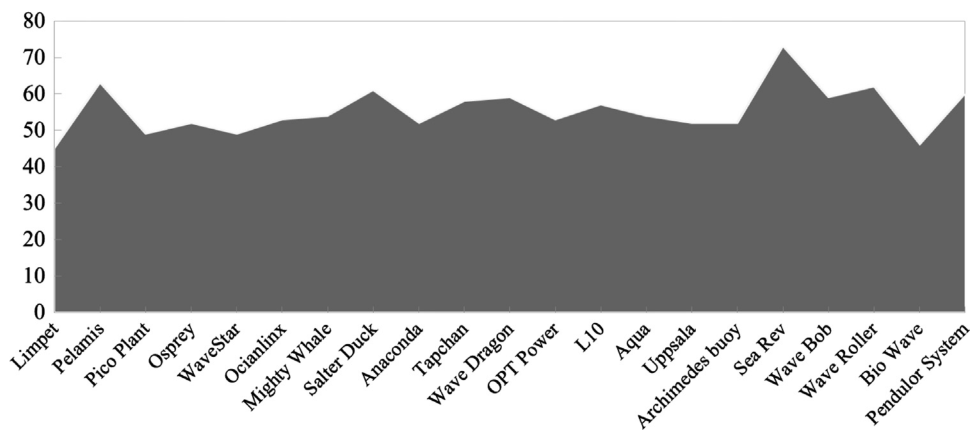


Fig. 8. The overall score of the systems for use in the Caspian Sea.

The most important technological characteristics include the materials, manufacturing technique, sealing, and generator technology.

Characteristics of the seabed also play an important role in choosing the most appropriate device. As discussed previously, the Caspian Sea has a relatively soft bed making it impossible to install and control any devices on the seabed as well as on its beaches. In addition, although the deployment of devices on the beach reduces the costs of maintenance and electricity transmission, they may damage the beach. Because the waves in the Caspian Sea have relatively small amplitudes, overtopping systems are not cost-efficient. In addition, systems that admit variable amplitude broadband waves from all directions are suitable.

Based on the current evaluation, the best device for implementation in the Caspian Sea is a system similar to SEAREV, Power Generating buoy, or Pelamis. The SEAREV system, a point absorber, was first introduced in 2002 by the French Institute École centrale de Nantes. The SEAREV consists of a mushroom-like floating structure. The mechanical and electrical systems are all contained by an outer shell. Also completely isolated by the shell is a relatively large pendulum that swings about a horizontal axis with no contact with the outside world. This system absorbs the oscillating energy of the wave and converts it into electrical energy. Once a wave strikes the outer body of the device, the pendulum wheel starts to rotate due to its inertia. This pendulum wheel is consisted of a gear coupled to two smaller ones. The rotational motion of the smaller gears is transferred to two pistons, which in turn pump a fluid. The pumped fluid drives a piston and thus rotates the rotor of an asynchronous generator.

Based on the current investigation, the SEAREV is selected as the first choice for harvesting wave energy in the Caspian Sea for a number of reasons. First, the mechanical and electrical components have no direct contact with the sea water, notably reducing the costs of maintenance and damages. Second, the presence of a relatively large pendulum with an off-center mass makes it capable of surviving extreme sea waves. Third, given that it is a floating system with no fixed connections, in the event of a mechanical or electrical failure, it can be dragged to the shore and repaired with minimal costs. This feature will make the SEAREV advantageous over fixed systems. Fourth, because of its pendular nature, the system reacts against gravity and remains self-referenced. A single cable is usually sufficient to keep the system in place. Fifth, given that the Caspian Sea has a soft and unstable bed, the SEAREV, as a floating device, has a clear advantage over other types of wave energy converters. Sixth, the SEAREV is equipped with a latching control system for the internal moving mass, allowing it to absorb the energy of a range of waves. Finally, this system is most appropriate for short wavelengths and medium height waves, characteristic of the waves observed in the Caspian Sea.

6. Conclusions

Existing wave energy conversion devices are evaluated to find the most appropriate system to harvest wave energy in the Caspian Sea. To achieve this goal, the most important design parameters as well as the main characteristics of the Caspian Sea are described. Each feature of the existing devices is assigned a score and presented in a benchmark table. The characteristics of the sea include its depth, the amplitude, wavelength and frequency of the waves along with the conditions of its bed and shore. Maintenance costs are also taken into account in the current investigation. Point absorbers are the most appropriate device for this sea. SEAREV, specifically is the most suitable converter for use in the Caspian Sea.

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